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CIRCULATORY ADJUNCTS: NEWER METHODS OF CARDIOPULMONARY RESUSCITATION

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Note: The author has no financial interest, consulting arrangement, or research contract with Ambu, CPRxLLC, or any other resuscitation device company, which could be construed as a conflict of interest.

SYNOPSIS

Current standard CPR only provides about one fifth of normal forward blood flow and only about one quarter of the blood flow that is theoretically possible with advanced external techniques. Two such techniques are now approved as optional alternatives in resuscitation guidelines. This chapter reviews modern understanding of the physiology of blood flow during CPR and practical aspects of utilizing more advanced resuscitation methods. When properly performed these methods produce statistically significant increases in survival.

INTRODUCTION

Conventional, what has come to be called standard, CPR has changed little since first introduced in the early 1960's by Kouwenhoven, Jude, and Knickerbocker¹. Standard CPR requires chest compressions at a rate of 80 to 100/min in conjunction with mouth-to-mouth rescue breathing². Positive pressure ventilations are given at an over all rate in the range of about 8 to 12/min, depending upon whether one is doing one-rescuer or two-rescuer CPR. Refinements of standard CPR since its introduction in the 1960's have included increasing the rate of chest compression from 60/min to 80/min or more, which research shows matters little³, and recently decreasing the tidal volume of the positive pressure ventilations under certain circumstances^{2,4}. Elimination of the carotid artery pulse check in the year 2000 guidelines has abolished unnecessary delay in starting chest compressions by lay rescuers. Otherwise, external CPR today is performed in just about the same way as it was in the 1960's. Not surprisingly, in keeping with the engineering maxim that "if you keep on doing what you're doing, you'll keep on getting what you've got", success rates for standard CPR have changed little over the past 40 years⁵⁻⁹. Between 15 and 40 percent of all victims of non-traumatic cardiac arrest are resuscitated, and about 5 to 10 percent live to leave the hospital.

Despite lack of significant change on the surface, a neglected community of researchers has made substantial progress in the laboratory and in the clinic during this same 40-year period. Results have lead to much fundamental understanding of the circulatory physiology and hemodynamics of cardiac arrest and resuscitation. A variety of alternative forms of CPR have been proposed and tested both in animals and in humans. All of these alternative methods apply more kinetic energy to the victim, either via an additional rescuer or some type of mechanical device. More energetic forms of CPR include high impulse CPR, interposed abdominal compression CPR, active compression-decompression, CPR, and vest CPR. These derivatives of standard CPR have come to be known as "circulatory adjuncts". By the year 2000 a convergence had occurred between laboratory knowledge about mechanisms of blood flow and clinical experience with the various adjuncts. This long delayed synthesis of research findings has led to improved forms of practical resuscitation based upon sound basic science principles. Here the term "improved" means "able to generate more blood flow and systemic perfusion pressure during cardiac arrest through the efforts of the rescuers". If there is one certain truth in resuscitation science, stemming from the pioneering work of Redding¹⁰, Ralston¹¹, Weil⁹, and Kern¹² it is this: improved coronary and systemic perfusion pressures during cardiac arrest and CPR lead to improved immediate resuscitation success and improved likelihood of longer term, neurologically intact survival.

The improved hemodynamics, however, do not come without a price, since more physical work has to be done by man or machine to generate more forward flow of blood. Accordingly, adjuncts may not be appropriate for the lone rescuer faced with a collapsed coworker or loved one. Nevertheless, the time has come for serious consideration of alternative forms of resuscitation when adequate equipment and trained personnel are available, for example, in the emergency department of a hospital. This chapter focuses on the relevant physiology of cardiac arrest and CPR that makes possible the generation of systemic perfusion pressure substantially greater than that provided by standard CPR. Thereafter, selected practical aspects of applying currently approved circulatory adjuncts in a hospital setting are discussed.

MODERN PHYSIOLOGY OF BLOOD FLOW DURING CPR

At least three different mechanisms can move blood during cardiac arrest and CPR. These are known as the cardiac pump, the thoracic pump, and the abdominal pump. The cardiac pump mechanism was the first to be recognized by the original discoverers of closed chest CPR¹. This pump mechanism is operative to the extent that external chest compression squeezes the cardiac ventricles between the sternum and the spine. As a result forward blood flow occurs through the aortic and pulmonic valves without mitral or tricuspid incompetence. In particular, when the cardiac pump mechanism is operative the aortic valve is open and the mitral valve is closed during chest compression¹³. The cardiac pump mechanism is also operative during open chest cardiac massage.

The thoracic pump mechanism was discovered in the 1980's as a result of Criley's clinical observation of cough CPR^{14,15} and extensive laboratory studies at Johns Hopkins University, led by Myron Weisfeldt and coworkers^{16,17}. This pump is operative to the extent that chest compression causes a global rise in intrathoracic pressure sufficient to force blood from the pulmonary vasculature, through the heart, and into the periphery. When the thoracic pump mechanism is operative both the mitral valve and the aortic valve are open simultaneously during chest compression¹⁸⁻²⁰. The heart acts as a conduit rather than a pumping chamber.

The abdominal pump mechanism was discovered independently by workers in Great Britain, Japan, Israel, and the United States in the latter half of the 20th century²¹⁻²⁶. This mechanism has two components: an arterial one and a venous one. The arterial component of the abdominal pump mechanism is operative to the extent abdominal compression forces blood from the abdominal aorta into the periphery against a closed aortic valve. Thus the aortic valve is closed during abdominal compression. The venous component of the abdominal pump mechanism is operative to the extent that external abdominal pressure forces blood from the inferior vena cava through the tricuspid valve into the right ventricle (or through both the tricuspid and pulmonic valves into the pulmonary vasculature). In this case the right heart valves are open during abdominal compression.

The operation of these three pumps—cardiac, thoracic, and abdominal—is related to the fundamental architecture of the cardiovascular system. The physiology of the pumps has been demonstrated in relatively simple mathematical models that represent the essential features of the human cardiovascular system^{24,27-31}. Successful circulatory adjuncts generate greater blood flow than standard CPR either by enhancing the operation of one of these pumps or by simultaneously invoking the action of multiple pumps. High impulse CPR, for example,³²⁻³⁴ aims to enhance the action of the cardiac pump mechanism. Vest CPR^{35,36} aims to enhance the action of the thoracic pump mechanism through the action of a pneumatic vest that is rapidly inflated and deflated at a rate of 60 to 150 times per minute. Active compression-decompression CPR^{37,38} aims to improve filling of either the cardiac pump or the thoracic pump by creating negative pressure in the thorax between chest compressions. Interposed abdominal compression (IAC)-CPR³⁹⁻⁴³ aims to invoke the abdominal pump together with either chest pump. Both IAC-CPR and its derivative, Lifestick CPR⁴⁴, aim to combine thoracic and abdominal pumps alternately, in such a

way that the thoracic pump primes the abdominal pump during one half of the cycle and the abdominal pump primes the thoracic pump during the other half of the cycle.

At this juncture the question naturally arises as to the relative effectiveness of these various adjuncts. It would be difficult indeed to compare and contrast all such methods in a single animal or clinical model. One reasonable and elucidating way to proceed, however, is to use a mathematical model of the circulation that includes all three pumps³¹. Such a model can be used to simulate the effects of various circulatory adjuncts in exactly the same circulatory system, without model-to-model variation. It can serve as well to demonstrate the relevant cardiovascular physiology of CPR.

An interesting feature of the circulatory model utilized in this chapter is the very small number of assumptions required to obtain realistic results³¹. These are limited to (1) the existence of compliant vessels and resistive vascular beds, (2) the definition of compliance ($\Delta V / \Delta P$), (3) normal anatomy, that is the arrangement of connected vessels and cardiac chambers, and (4) a linear relation between flow and pressure ("Ohm's Law": flow = pressure / resistance). Although much more complex models of the circulation can be created, only these basic assumptions are needed to demonstrate the three mechanisms of blood flow during CPR and the relative utility of various circulatory adjuncts. Circulatory systems that have these properties will behave similarly, including those of large and small people and large and small experimental animals. Accordingly, I shall use this simplest realistic model of CPR physiology, to illustrate the actions of the basic pump mechanisms and to demonstrate selected circulatory adjuncts. The exact values of vascular compliances and resistances, as well as other technical details of the model, which can be implemented in a Microsoft Excel spreadsheet, are fully described elsewhere³¹.

As a point of reference and calibration, Figure 1 (end of manuscript) illustrates pressures throughout a simplified cardiovascular system for a non-arrested circulation of a hypothetical 70 kg man. Here a cardiac pump generates left ventricular pressures (P_{pump}) of 122/2 mmHg at a heart rate of 80/min. Systemic arterial blood pressure is 119/82^{**}, mean arterial pressure is 95 mmHg, and cardiac output is 5.0 L/min. These are classical textbook values for the normal human circulatory system³¹. Note the essentially normal arterial pulse waveforms and low systemic venous pressures.

Figure 2 illustrates the action of a pure cardiac pump CPR in the same circulatory model during cardiac arrest. Steady-state conditions are shown after stable pressures have been achieved by 20 prior compressions. In this simulation only the right and left ventricles of the heart are compressed at a rate of 80/min with a half sinusoidal waveform having a peak pressure of 60 mmHg, a typical value reported in the literature of standard CPR²⁹. There is no intrinsic myocardial contractility in this system, and there is no pump priming effect of atrial contraction (which in some circumstances could exist for a few minutes in witnessed cardiac arrests). The cardiac pump produces reasonable aortic pressures and very small venous pulsations. Note especially the low right-sided central venous pressures throughout the compression cycle. There is substantial coronary perfusion pressure (aortic to right atrial gradient) throughout the cycle.

^{**} The data point representing the exact minimum, diastolic pressure at 82 mmHg is not plotted on the chart.

Forward flow is 2.5 L/min, and systemic perfusion pressure is 47 mmHg. This state of affairs represents idealized classical external CPR in which “the heart is squeezed between the sternum and the spine” as reported in 1965 by DelGuercio⁴⁵. It is also a reasonable representation of open chest CPR with manual cardiac compression, which obviously works by a pure “cardiac pump” mechanism. A similar state of affairs can occur in children (and young pigs^{46,47}), who have small compliant chest walls.

Figures 1 through 2 were generated using positive applied extravascular pressures during the compression phase and zero extravascular pressure during the relaxation phase. A relatively recent concept in the physiology of CPR is the use of active decompression, rather than simple relaxation, between chest compressions. Decompression can be accomplished by the use of “plunger like” devices (discovered accidentally using a real toilet plunger!^{48, 37}) or by sticky adhesive pads that make contact with the skin of the anterior chest or abdomen such as those incorporated into the Lifestick⁴⁴. This approach is known as active compression-decompression CPR or ACD-CPR (Figure 3). Today, active decompression of the chest during CPR can be accomplished using a specially designed plunger applied to the human sternum^{46,49-51}, which is sold commercially in Europe as the Ambu Cardiopump[®].

Figure 4 illustrates the steady-state effect of active decompression of the chest to negative 20 mmHg, the maximum reported in the literature^{50,52,53}. This particular simulation is for cardiac pump CPR. Combining both positive and negative chest pressures has a salubrious effect upon hemodynamics. Cardiac filling is enhanced during the negative pressure phase, so that greater stroke output can be achieved on the next positive pressure phase. Note in Figure 4 the particular times near 0.55 seconds in the cycle when pump pressure is substantially less than right heart pressure. At this stage enhanced pump filling occurs. The result of enhanced pump filling is greater forward flow and greater perfusion pressures—3.2 vs. 2.5 L/min and 61 vs. 47 mmHg. When more energy is applied to the arrested circulation in this manner, forward flow improves. A potential advantage of the use of negative and positive pressure phases, rather than simply greater positive pressure, is that it is less traumatic to the victim. Also needless compression of pumping chambers that are already empty is avoided. As will soon be seen, the use of a decompression phase compliments the use of a compression phase for all three pump mechanisms in CPR.

When it works, the cardiac pump mechanism is the most effective and natural of the three pumps in CPR. Its operation in external CPR, however, depends upon good mechanical coupling between the sternum and the heart. In most adults the coupling of chest compression to the heart is indirect, and a thoracic pump mechanism tends to predominate^{20,35,54}. Thoracic pump CPR has a quite different set of pressure profiles. Figure 5 illustrates the action of a pure thoracic pump. In this simulation all intrathoracic blood containing chambers are pressurized equally at a rate of 80/min with a peak pressure of 60 mmHg, as before. This state of affairs happens in broad chested adults. It also happens during vest CPR, in which a pneumatic vest encircles the chest to produce pulses of compression from all sides simultaneously.

In thoracic pump CPR forward flow occurs even though the heart is not being squeezed between the sternum and the spine. Coronary blood flow and systemic blood flow occur when aortic pressure is greater than systemic venous or right heart pressure. As shown in Figure 5,

positive coronary and systemic perfusion pressures occur mostly between compressions, rather than during compressions. Because of the tendency toward equalization of aortic and venous pressures during compressions, forward flow with the thoracic pump mechanism tends to be less, other factors being equal, than with the cardiac pump mechanism. In a thoracic pump model of Figure 5 forward flow is 0.94 L/min and systemic perfusion pressure is 18 mmHg.

If a decompression phase is added (Figure 6), perfusion pressures are somewhat increased, but to a lesser extent than with cardiac pump CPR. Here forward flow is 1.14 L/min and systemic perfusion pressure is 22 mmHg. The difference in the responsiveness of the thoracic and cardiac pumps to negative pressure priming may be responsible for some of the discrepancies in the reported literature regarding the benefits of active compression-decompression CPR in various models³¹. The simulated improvement in coronary perfusion pressures with ACD-CPR (61 mmHg for a cardiac pump model and 22 mmHg for a thoracic pump model) are in keeping with the range of measured coronary perfusion pressures in human patients during ACD-CPR. In one recent study⁵¹ the generation of -20 mmHg intrathoracic pressure during ACD was insured with the use of an inspiratory impedance valve. These investigators found coronary perfusion pressures of 40 to 45 mmHg. These results are consistent with those of Figures 4 and 6, if one takes the modern consensus view^{20,35,54} that the operative pump mechanism in different animal and clinical models is a combination of the cardiac and thoracic pumps.

Figure 7 illustrates the steady-state action of a pure abdominal pump. In this simulation there is no chest compression. Abdominal compression begins at time zero. Only the abdominal aorta and vena cava are compressed at a rate of 80/min with a pressure of 110 mmHg, values reported in the literature of IAC-CPR^{39,55,56}. Manual compression leading to periaortic pressures this high can be tolerated without pain by a conscious person⁵⁷. Artificial circulation can indeed be created by abdominal compression only, as first observed experimentally by Rosborough, Niemann, and coworkers⁵⁸. During abdominal compression blood is squeezed from the aorta to the periphery by the positive intra-aortic pressure acting against a closed aortic valve. During abdominal relaxation the aortic valve opens, allowing filling of the aortic pumping chamber from the left heart and lungs. Only one valve is needed to achieve forward flow, as can be demonstrated by deliberately rendering the other three heart valves incompetent²⁹. Note that the abdominal aortic pressure waveform at 0 to 0.2 sec in the cycle leads the thoracic aortic pressure waveform in time, indicating retrograde flow in the aorta. Pump pressures change very little, because the chest pump is acting as a passive conduit. There is a positive coronary perfusion pressure during most of the compression cycle. Forward flow is 1.3 L/min and coronary perfusion pressure is 25 mmHg.

Figure 8 shows the potential benefit of adding active abdominal decompression (-20 mmHg pulses) to abdominal compression. Such a manipulation is possible using a sticky adhesive abdominal pad, and has been implemented practically in the experimental Lifestick[®] device. In this simulation there is still no chest compression. The abdominal pump is filling when chest pump pressure is greater than thoracic aortic pressure near 0.4 seconds in the cycle. At this time the low resistance aortic valve is open. With active abdominal decompression the filling pressure differences are more obvious than when abdominal decompression is absent. During subsequent abdominal compression positive pressure in the aorta, which is greater than

that in the chest pump, closes the aortic valve. The slower rise of right heart pressures compared to inferior vena cava pressures is associated with differences in the capacitances of these structures. Near 0.3 seconds of the cycle the chest pump, including the heart and lungs, fills when right heart pressure exceeds chest pump pressure. Thus forward flow occurs around the entire circuit with abdominal compression/decompression alone. As in the case of the cardiac and thoracic pumps, the addition of active decompression enhances abdominal pump performance (Figure 8).

COMBINING CHEST AND ABDOMINAL PUMPS

Given this theoretical background, it is a very small conceptual leap to imagine combining both chest and abdominal pump mechanisms. The most simple and practical such combination is called interposed abdominal compression CPR (Figure 9). Interposed abdominal compression CPR invokes the abdominal pump together with either the cardiac or thoracic pump. The trick is to compress the abdomen during chest diastole, thereby operating two pumps together in the same compression cycle. Alternation of chest and abdominal compression has the practical advantage of avoiding trauma to the liver, and has been proved extremely safe in animal and human trials⁴³. Although other timing and phasing schemes have been investigated^{23,30,44} the simplest and most studied form of interposed abdominal compression CPR (IAC-CPR), involves a 50 percent duty cycle for both chest and abdominal phases. That is, the compression cycle is divided into two equal duration phases, in which an extra rescuer manually compresses the abdomen during the relaxation phase of chest compression^{26,42}. With alternating chest and abdominal compression the aortic valve is open during chest compression and closed during abdominal compression. Chest pump outflow during chest compression fills the aorta, priming the abdominal pump. Abdominal-to-thoracic caval flow during abdominal compression fills the right heart and pulmonary vasculature, priming the chest pump³¹. Thus the two pumps work in concert. Improved venous return increases stroke output of the chest pump, in conjunction with either the thoracic pump mechanism or direct cardiac compression. Abdominal compression also produces counterpressure on the abdominal aorta, inducing retrograde flow toward the heart and brain between chest compressions⁵⁹. This abdominal pump action on the arterial side increases flow in a manner analogous to an intra-aortic balloon pump^{29,43}.

The effectiveness of such combined chest and abdominal compression was discovered empirically^{22,26} long before the theoretical physiology had been worked out²⁷⁻³¹. Indeed the positive hemodynamic effects of IAC during CPR have been confirmed in 20 of 21 animal studies using canine and porcine models, most of which are reviewed in references⁴³ and ⁶⁰. After encouraging laboratory studies, clinical trials of IAC-CPR were done. Three randomized clinical trials of IAC-CPR for in-hospital cardiac arrest have shown statistically significant improvement of outcome measures^{42,61,62}. One randomized trial of pre-hospital IAC-CPR, combined, when possible, with standard CPR in the field, showed no difference in outcome⁶³. These studies are summarized in Table 1. Pooled analysis of all available data for both pre-hospital and in-hospital resuscitations shows statistically significant improvement in the return of spontaneous circulation with IAC-CPR. When only in-hospital studies are examined, the effect of IAC becomes much greater and is highly statistically significant. Pooled data from two studies that examined long term, neurologically intact survival following in-hospital

resuscitations show a positive benefit of IAC-CPR compared with standard CPR. Thus strong pre-clinical and clinical evidence supports the use of IAC-CPR for in-hospital resuscitations.

Table 1: RESULTS OF CLINICAL STUDIES OF IAC-CPR VS. STANDARD CPR

Outcome Measure	Studies	IAC-CPR	Standard CPR	P-value
Return of spontaneous circulation in or out-of-hospital	Mateer ⁶¹	40/145 (28%)	45/146 (31%)	0.54
	Ward ⁵⁹	6/16 (38%)	3/17 (18%)	0.19
	Sack ³⁹	29/48 (60%)	14/55 (25%)	0.00014
	Sack ⁶⁰	33/67 (49%)	21/76 (28%)	0.0067
	All 4 studies	108/276 (39%)	83/294 (28%)	0.0056
Return of spontaneous circulation after in-hospital resuscitation	Ward ⁵⁹	6/16 (38%)	3/17 (18%)	0.19
	Sack ³⁹	29/48 (60%)	14/55 (25%)	0.00014
	Sack ⁶⁰	33/67 (49%)	21/76 (28%)	0.0067
	All 3 studies	68/131 (52%)	38/148 (26%)	0.000003
Survival to discharge, neurologically intact after in-hospital resuscitation	Ward ⁵⁹	1/16 (6%)	0/17 (0%)	0.3017
	Sack ³⁹	8/48 (17%)	3/55 (5%)	0.0700
	Both studies	9/64 (14%)	3/72 (4%)	0.0453

For the purpose of the present discussion the hemodynamic benefits of IAC-CPR can be demonstrated in the same mathematical model with which we investigated basic physiology. Figure 10(a) illustrates the addition of 110 mmHg interposed abdominal compressions to 60 mmHg peak thoracic compressions in a cardiac pump model. Here the cardiac and abdominal pump mechanisms are combined. (Even though more external force is applied to the chest than to the abdomen in practice, typical intrathoracic pressure pulses are less than intra-abdominal pressure pulses because of the stiffness of the chest wall.) The double arterial pressure peaks in Figure 10(a) attest to the effects of the double pump approach. Systemic perfusion pressure is sustained throughout both phases of the compression cycle. Enhanced filling of the chest pump is evident at cycle times near 0.7 seconds. Filling of the abdominal pump chamber—that is the aorta—can be seen at cycle times near 0.125 seconds. The increased forward flow in this model 3.6 L/min with IAC versus 2.5 L/min for cardiac pump CPR. Systemic perfusion pressure is 68 mmHg vs. 47 mmHg for cardiac pump CPR. Thus the ratio of perfusion during IAC-CPR to perfusion during standard CPR is 1.44 in a pure cardiac pump model.

Figure 10(b) illustrates the addition of 110 mmHg interposed abdominal compressions to 60 mmHg peak thoracic compressions in a pure thoracic pump model, illustrating similar effects of the double pump approach when the thoracic and abdominal pump mechanisms are combined. The increased forward flow in this model 2.1 L/min with IAC versus 0.93 L/min for thoracic pump CPR. Systemic perfusion pressure is 39 mmHg vs. 18 mmHg for thoracic pump CPR. Thus, there is a roughly two-fold ratio of perfusion during IAC-CPR to perfusion during standard

CPR in a thoracic pump model versus a roughly 1.5 fold ratio of perfusion during IAC-CPR to perfusion during standard CPR in a cardiac pump model. If one takes the modern consensus view^{20,35,54} that the operative pump mechanism in different animal and clinical models is a combination of the cardiac and thoracic pumps, these simulation results agree perfectly with the aggregate results of laboratory and clinical research on IAC-CPR, in which systemic perfusion pressure or carbon dioxide excretion served as measures of overall forward flow^{26,43,59, 61}. These research studies found a 1.5 to 2-fold improvement in perfusion with the addition of IAC.

The safety of interposed abdominal compressions, as reviewed previously⁴³, has been well documented in 426 humans, 151, dogs and 14 pigs. Only one isolated case report of traumatic pancreatitis in a child⁶⁴ describes local trauma from abdominal compression during CPR. These data compare favorably with the well-known and frequent incidence of rib fracture and pulmonary contusion from chest compression during CPR⁶⁵⁻⁶⁷. Increased emesis and aspiration from IAC have not been reported, and there is even evidence that if positive abdominal pressure is applied during ventilations from the beginning of an arrest, the rate of gastric inflation before endotracheal intubation is reduced⁶⁸.

Can we do even better? Theory suggests that the answer is “yes”. Ordinary IAC-CPR, as studied experimentally over the past 20 years, includes only positive pressure compressions without active decompression. A logical extension of this line of thought is to examine full 4-phase CPR, which includes active compression and active decompression of both the chest and the abdomen. All four phases can be accomplished in a single cycle, because chest compression and abdominal decompression can be accomplished simultaneously in the first half of the cycle, and abdominal compression and chest decompression can be accomplished simultaneously in the second half of the cycle.

Recently a commercial venture has attempted to implement this concept in a device called the Lifestick[®] (Figure 11). The Lifestick[®] is a mechanical device under development, with which one person can perform both chest and abdominal CPR. Compression is applied through a rocker arm with adhesive pads attached to the chest and the abdomen. The broad chest compression pad of early models precludes cardiac pump mechanism, but also obviates rib fracture. Because the chest and abdominal pads are adhesive, it is possible to obtain a measure of upward retraction of the chest during the abdominal compression phase and *vis versa* by a rocking motion of the device. Such a device in principle has the advantage of permitting active compression and decompression of both chest and abdomen³¹.

The hemodynamic potential of such 4-phase CPR is illustrated in Figure 12. Figure 12(a) shows cardiovascular pressures during cardiac pump and abdominal pump CPR with active compression and decompression. The 4-phase method produces dramatically large pressure fluctuations in the chest and abdominal vascular compartments, although the external compression forces are no different than those used for standard CPR or conventional IAC-CPR, and the applied external decompression forces are substantially less than the compression forces. Nearly normal systemic perfusion pressures are obtained throughout the cycle. There is no restriction of positive coronary and systemic perfusion pressure to the diastolic phase. Forward blood flow is 4.6 L/min, approaching the textbook value of 5.0 L/min for the normal circulation in a 70 kg man. These levels are a far cry from the 20 percent of normal forward flow we have

come to expect from standard CPR^{69, 70}. Routine practical implementation of full 4-phase CPR has yet to be achieved, partly as a result of legal and commercial wrangling unrelated to science and engineering. However, animal studies with a prototype Lifestick[®] device are encouraging⁴⁴.

The forgoing survey of resuscitation physiology suggests a significant potential for improvement of current CPR through the application of combinations of both positive and negative pressure to both the chest and the abdomen. The most recent American Heart Association guidelines for CPR and emergency cardiovascular care² permit the judicious use of two advanced forms of CPR at the discretion of a physician under conditions in which adequate equipment and trained personnel are available. These approved adjuncts include IAC-CPR and active compression-decompression, or ACD-CPR. As so-called "Class IIb" interventions both IAC and ACD-CPR are considered within the "standard of care", which reasonably prudent physicians can choose to use⁷¹. They are considered optional or alternative interventions by a majority of experts. Technically both could be done together under the guidelines in selected clinical settings to achieve at least a 3 phase CPR, which has hemodynamic benefits nearly as great as 4-phase CPR³¹. This new state of affairs, in which emergency department physicians have considerable professional discretion, brings us to consider practical aspects of implementing the new CPR adjuncts.

PRACTICAL ASPECTS OF ACTIVE COMPRESSION-DECOMPRESSION CPR

ACD-CPR requires use of a plunger like device, sold as the Cardiopump[®] or ResQ-Pump[™]. With a two-handed grip on the handles of the device, a rescuer can apply both active compression and decompression. Teams in Europe, especially in Paris, have been trained to use the Cardiopump with good results, including improved survival at one year after resuscitation compared to standard CPR⁷². Some studies have reported mixed results with the Cardiopump⁷³⁻⁷⁷, perhaps as a result of less intensive training^{78,79}. Those considering use of ACD-CPR are advised to train well in the use of the device and repeat training often⁷⁸. Training mannequins and other educational materials are available from the manufacturer.

At the time of this writing the Ambu Cardiopumps are not approved for use in the United States by the U.S. Food and Drug Administration. They are commercially available outside the United States and are manufactured by Ambu, Inc. (Glostrup, Denmark) and marketed in the Western Hemisphere by CPRxLLC (Minneapolis, Minnesota). The Cardiopump weighs 0.58 kg and costs about \$300. The vacuum cup is 135 mm in diameter and is made of soft silicone rubber. It can be removed for cleaning and for autoclave sterilization after use. The vacuum cup is not electrically conducting and does not interfere with transchest electrical defibrillation. It has been designed to adhere to a variety of chest anatomies, including wet hairy skin without losing contact with the chest wall during decompression. Earlier models did not work well on women with larger breasts^{80, 81}, and the cup may still seal poorly in about 10 percent of women.

Rescuer fatigue is a known problem with ACD-CPR, since it takes more energy to do active compression decompression than to do active compression alone^{79,82}. Back fatigue is definitely reduced if the rescuer either kneels beside the thorax of the victim or works astride the victim on his or her knees. A blanket or pillow under the knees of the rescuer may allow the

rescuer's arms and back to be straighter when using the Cardiopump device⁷². Since the handle is offset from the chest by about 15 cm, the rescuer's shoulders need to be "higher" over the victim than in conventional CPR. If the patient is raised on a table, a stool may be needed by the rescuer to provide the necessary elevation.

In using a Cardiopump the arms should be straight and the back of the rescuer as close to vertical as possible. The elbows should be locked. Wrists should be firm, as in gripping a tennis racquet. In this position the rescuer can work effectively by raising and lowering the hips against gravity. As the rescuer's hips are lowered in the kneeling position, the weight of the rescuer's body can be used to apply compression. As the rescuer's hips are raised, the quadriceps muscles of the anterior thigh can work to apply decompression while the rescuer's arms remain straight^{**}. Posterior compartment (hamstring) muscles and the gluteus maximus muscles are active as well in the kneeling position. Reliance upon the large anterior and posterior thigh muscles and gluteus muscles minimizes fatigue and keeps the exercise aerobic for either male or female rescuers. These same muscles should be used as much as possible in the standing position as well, to minimize fatigue. Upper body strength is not required, once rescuers learn to use leg muscles and NOT back muscles. Nevertheless, adequate personnel need to be available so that frequent changes can occur every 3 to 5 minutes to avoid fatigue.

As fatigue sets in, rescuers tend to revert to former habitual methods of chest compression without decompression, and the benefits of ACD-CPR are lost. Remembering to lift up during each cycle is the most challenging aspect of using a Cardiopump device. A force gauge on the handle indicates the target ranges of compression and decompression force for chests of "soft", "normal", or "stiff" characteristics. The gauge provides useful biofeedback. The duty cycle for ACD-CPR is 50% compression time, 50% decompression time. Further details of ACD-CPR methodology and training are described by Wik et al.⁷⁸.

A major potential improvement in ACD-CPR is the use of an inspiratory impedance valve⁴⁶ for victims with an established endotracheal tube⁵¹. This valve fits on the end of the endotracheal tube and prevents "decompression of the decompression", that is, an inrush of air into the trachea during the active decompression phase. The resulting increase in the magnitude of the intrathoracic decompression encourages even more chest pump priming. The valve incorporates a "pop-off" feature that is set to open when the intrathoracic pressure decreases below - 22 cm H₂O. The valve prevents inflow only when intrathoracic pressure is zero to 22 cm H₂O negative with respect to atmospheric pressure. It does not interfere with normal positive pressure ventilations or with vigorous spontaneous negative pressure ventilations, if the patient begins to gasp strongly enough to create at least 22 cm H₂O negative pressure. However, if a pulse returns, the ResQ-Valve should be immediately removed and the ventilation source reattached to the airway to allow normal spontaneous breathing. The inspiratory impedance valve is available commercially as a resuscitation device called the ITV Resusci-Valve or ResQ-ValveTM (CPRxLLC, Minneapolis, Minnesota). It is a disposable device that costs between \$30 and \$50.

^{**} The reader is encouraged to try this motion in the kneeling position while palpating the quadriceps, gluteus maximus, and hamstring muscles. Note that when the hips are raised when kneeling, the leg is extended at the knee joint by the quadriceps and the thigh is extended at the hip joint by the hamstrings.

PRACTICAL ASPECTS OF INTERPOSED ABDOMINAL COMPRESSION CPR

From a practical standpoint, the simplest, least expensive, and longest studied CPR adjunct is IAC-CPR. This method is essentially device-less. There is no equipment cost, and there is no requirement for FDA approval. It can be performed by two hands of a third rescuer, as shown in Figure 9. IAC-CPR is especially appropriate for in-hospital resuscitations, where the dictum “When extra hands are free, do IAC” may well apply. IAC-CPR is most easily performed when the rescuers compressing the chest and abdomen are on opposite sides of the patient. Since the most favorable clinical results have been obtained when IAC-CPR is applied from the beginning of resuscitation, early application of the technique is to be encouraged. Use of IAC-CPR as a last-ditch effort after prolonged, failed ACLS is not recommended and has not been shown to be effective⁶¹. Obviously, IAC is not recommended for pregnant women, persons suspected of having an abdominal aortic aneurysm, or persons known to have had recent abdominal surgery.

The abdominal compression technique in IAC-CPR involves rhythmic, manual compression of the mid-abdomen. The abdominal compression point is located in the midline, halfway between the xiphoid process and the umbilicus. The recommended force of abdominal compression is that sufficient to generate approximately 110 mmHg external pressure on the abdominal aorta and vena cava and is equivalent to that required to optimally palpate the aortic pulse in a patient or volunteer when the heart is beating normally⁸³. The technique for compression of the abdomen is similar in most respects to the technique for compression of the chest.

Hand Position and Compression Technique

The umbilicus should be visible and not covered by the compressing hands. Just as chest compression is applied making contact with the heel of one hand, which is covered by the heel of the other hand, abdominal compression is applied in the same manner. The heel of the rescuer’s bottom hand should lie along the midline of the abdomen. This midline position will keep the main force of compression over the abdominal vena cava and aorta. The fingers may be either extended or interlaced but should be kept off the abdomen.

A straight-armed abdominal compression technique, similar to that used for chest compression, is ergonomically effective. Because the abdomen is comprised of soft tissues without the bony resistance of the rib cage, adequate compressions do not require strong muscular effort. In practical training students will learn the force required to produce safe and effective 110 mmHg pressure pulses within the abdomen. The depth of abdominal compression is not unlike that of chest compression, 1 ½ to 2 inches, in a normal sized, non-obese adult. For obese patients greater compression depth may be necessary. Compressions can be delivered to the abdominal compression point straight down in the vertical plane, or to maximize aortic counterpulsation, from the left side of the victim at 11 degrees left of vertical⁸³. In principle, when IAC-CPR is properly performed the carotid or femoral pulse will demonstrate double peaks, denoting both chest and abdominal compressions^{31,55}. The clinical utility of assessing a double pulse in this setting, however, has not been investigated.

Coordination of Chest and Abdominal Compressions

The rhythm of abdominal compression is natural and as easy to learn. If the chest compressor counts “one – AND – two – AND – three – AND ...”, the abdominal rescuer applies pressure during “AND” and releases pressure during each counted number. The release of abdominal pressure between chest compressions is needed for chest and abdominal pump mechanisms to work together³¹ and also to avoid entrapment of the right lobe of the liver under the sternum when the chest is compressed. Thus, abdominal pressure should be applied whenever chest compressions are relaxed, and abdominal pressure should be relaxed whenever chest compressions are applied. Abdominal pressure can be maintained during ventilations to minimize gastric inflation if no endotracheal tube is in place⁶⁸. The most widely used and tested duty cycle is 50% chest / 50% abdominal compression time. There is some theoretical advantage to 30% chest, 70% abdominal compression time³⁰, but this variation has not yet been tested in humans.

If two-rescuer CPR has been established and a third rescuer becomes available, this person should take a position on the opposite side of the patient from the second rescuer who is performing chest compressions, locate proper hand position, sense the rhythm of chest compressions, and begin then interposed abdominal compressions. If rescuers doing chest and abdominal compressions wish to switch positions (abdominal compressions are less tiring, because there is no rib-cage resistance) it is natural for them to slide headward and foot-ward, respectively, during a ventilation, since they are on opposite sides of the patient.

Training Individuals to do IAC-CPR

A detailed analysis of the ergonomic complexity of interposed abdominal compression (available from the author on request) suggests that it is no more complicated to learn and perform than is opening an airway. The following modifications of whole body mannequins for teaching three-rescuer IAC-CPR are easily done and are inexpensive.

1. Add extra foam rubber to the lower thoracic compartment of the mannequin and to the abdominal compartment to simulate subcostal soft tissues.
2. Wrap a standard blood pressure cuff around a towel and place it in the abdominal compartment beneath the abdominal compression point (5-cm headward of the umbilicus) in the midline. Bring the tubing, aneroid manometer gauge, and squeeze bulb out at belt-line of the mannequin so that the gauge is visible to the trainees. Tape target pressure markers on the manometer dial at 120 mmHg. Inflate cuff to a resting pressure of 10 mmHg.
3. During practice sessions coach trainees to hit the target pressure during IAC. The issue of how hard to press has been addressed in detail elsewhere⁸³.

If a mannequin is not available, a rolled blood pressure cuff placed inside a rolled towel is a useful training model. Successful practice sessions can be conducted in as little as five minutes. The following sequence may be used.

1. The abdominal rescuer takes position on opposite side of victim from chest compressor.

2. Chest compressor says, “You press here (pointing to the abdominal compression point) whenever I release.”
3. Chest compressor counts “one – AND – two – AND – three – AND ...”. Abdominal rescuer applies pressure during “AND”.
4. Start with slow-motion practice and then gradually increase to a normal compression rate. With this kind of practice session, health care professionals can be taught to do interposed abdominal compression with little time or trouble.

Combining IAC with ACD-CPR

In selected research settings there is good reason to investigate combining the methods of ACD and IAC-CPR to create 3-phase CPR. Such a method is practically achievable with current technology, omitting only the fourth phase, active abdominal decompression, from full 4-phase CPR. Advance experience with the two techniques separately, would of course be prudent before attempting to combine them. Moreover, full consideration of the following warnings and caveats is in order.

WARNINGS ABOUT THE GENERAL USE OF CIRCULATORY ADJUNCTS

Because of the requirement for special training and sometimes special equipment, advanced forms of CPR are best performed in a hospital by trained health care providers.

Endotracheal intubation is prudent before instituting CPR adjuncts. Most studies of IAC-CPR have required that an endotracheal tube be in place for fear of regurgitation in response to IAC (a fear not substantiated by data⁴³). Similarly, an endotracheal tube is desirable if ACD-CPR is performed with an inspiratory impedance valve. The valve can be used with a tightly sealed face mask, but extra care must be taken to avoid leaks.

It is extremely important in one's enthusiasm for CPR adjuncts NOT to delay electrical ventricular defibrillation when VF is present. New data confirm the old^{84,85} that if ventricular fibrillation has been present for less than 4 to 5 minutes, electrical defibrillation is clearly the treatment of choice. For longer “down times” however, there is evidence that a vasopressor drug plus effective CPR, which produces good coronary perfusion pressure prior to shock, can indeed improve resuscitation success. Here is a situation in which enhanced CPR methods such as IAC-CPR can potentially benefit patients in the hands of trained healthcare providers.

If initial shocks are not successful for VF, institute adjuncts early--NOT as a last resort after failed ACLS. Adjuncts do not work on dead people. Their use after failed ACLS will only lead to unjustified cynicism.

With more powerful and effective CPR modalities one can expect an increased number of ROSC's and an increased number of discharge survivals^{72,86}. However, one must also expect an increased number of individuals who survive only briefly. It is probably unavoidable result of multiplied probabilities that in addition to greater numbers of saves, there will be greater numbers of people who will be resuscitated only to run up expensive hospital bills for a day or so

and then die. It is even possible, although not yet shown by published data, that more effective techniques of resuscitation might produce increased numbers of individuals resuscitated to a lingering vegetative state. Clinical experience with the new modalities will be needed to determine which individuals are at greatest risk for this most undesirable outcome. IAC or ACD-CPR cannot change underlying pathology or control the quality of care after resuscitation. There is however, theoretical, experimental, and clinical evidence that these improved, more energetic, and more aggressive resuscitation methods can improve blood flow during CPR, and in turn the probability of neurologically intact short term and long term survival.

CONCLUSIONS

Principles of cardiovascular physiology tell us that during cardiac arrest and CPR forward flow of blood can be generated by external compression or decompression of either the chest or the abdomen. Standard CPR utilizes only one of these modes—chest compression—and generates roughly 1 L/min forward flow in an adult human⁴⁵, which is 20 percent of normal cardiac output. Interposed abdominal compression CPR utilizes two of these modes—chest compression and abdominal compression—and generates roughly twice the forward flow, or 2 L/min in an adult human⁶¹. Active compression-decompression CPR utilizes two of these modes—chest compression and chest decompression—and also generates roughly twice the forward flow as standard CPR⁵¹, although the results are somewhat model dependent. The studies of Sack with IAC-CPR and of Plaisance^{72,86} with ACD-CPR suggest that when methods that double perfusion are methodically employed, resuscitation outcome in terms of short term and long term survival are also roughly doubled^{72,86}. This state of affairs is fortunate, since it is quite possible that factors such as severe underlying disease or the quality of post-resuscitation care could blunt or cancel positive effects of improved blood flow during the brief resuscitation period. Theoretically, full 4-phase CPR, including active compression and decompression of both chest and abdomen, is capable of generating 4 L/min forward flow or greater, which is 80% of normal, and there is a reasonable prospect of achieving 100 percent of normal flow under conditions in which all four phases are optimized⁸⁷. Standard CPR is clearly not the ultimate form of external cardiopulmonary resuscitation. There is real, credible evidence that substantial improvements in resuscitation methods and results will be possible in the next decade.

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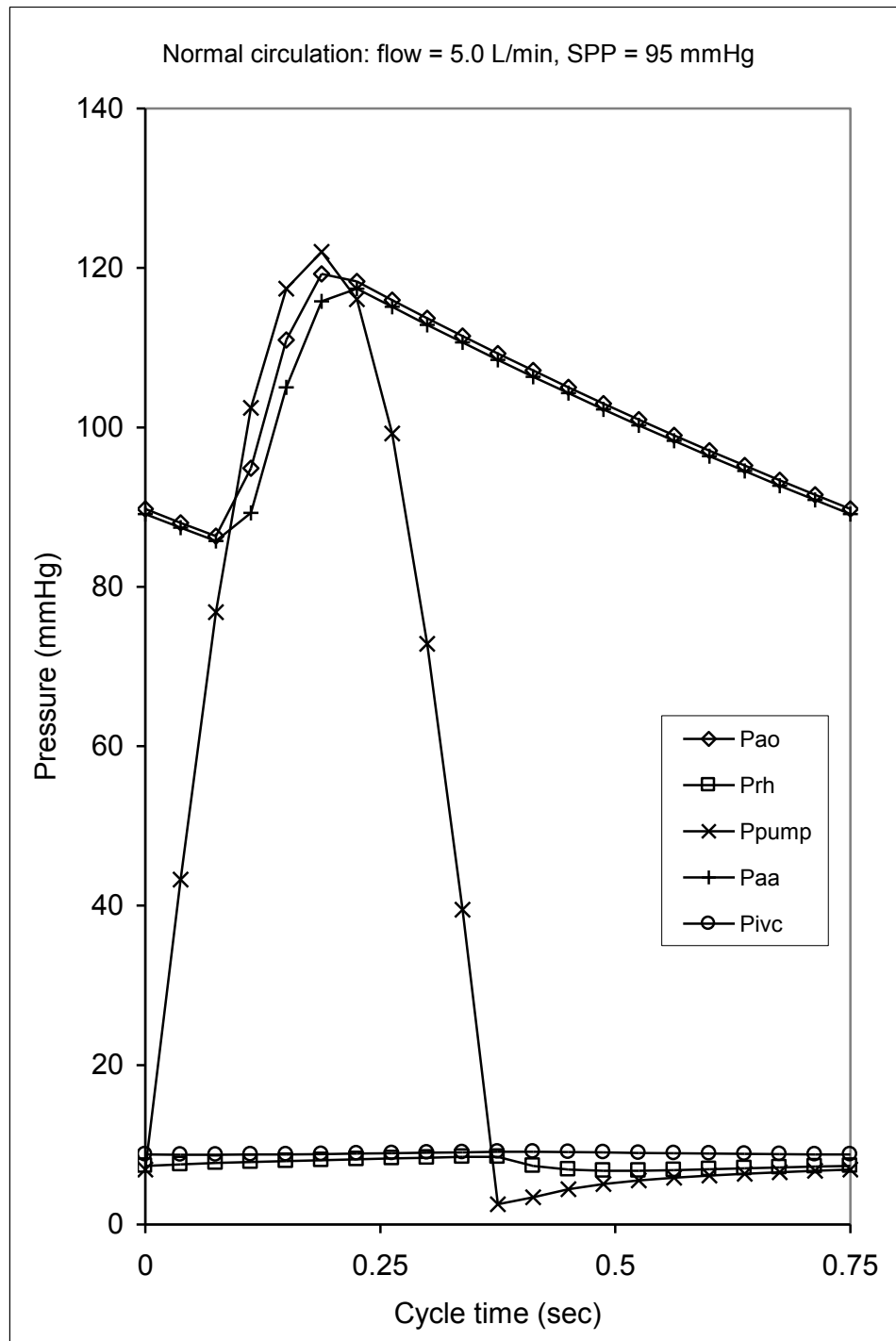


Figure 1. Pressures in a mathematical model of the normal adult human circulation with the cardiac ventricles beating. The heart rate is 80/min. Pressures are plotted as a function of cycle time for the thoracic aorta, Pao; the right atrium, Prh; the intrathoracic pump, here the left ventricle, Ppump; the abdominal aorta, Paa; and the inferior vena cava, Pivc. SPP is mean systemic perfusion pressure = Pao minus Prh.

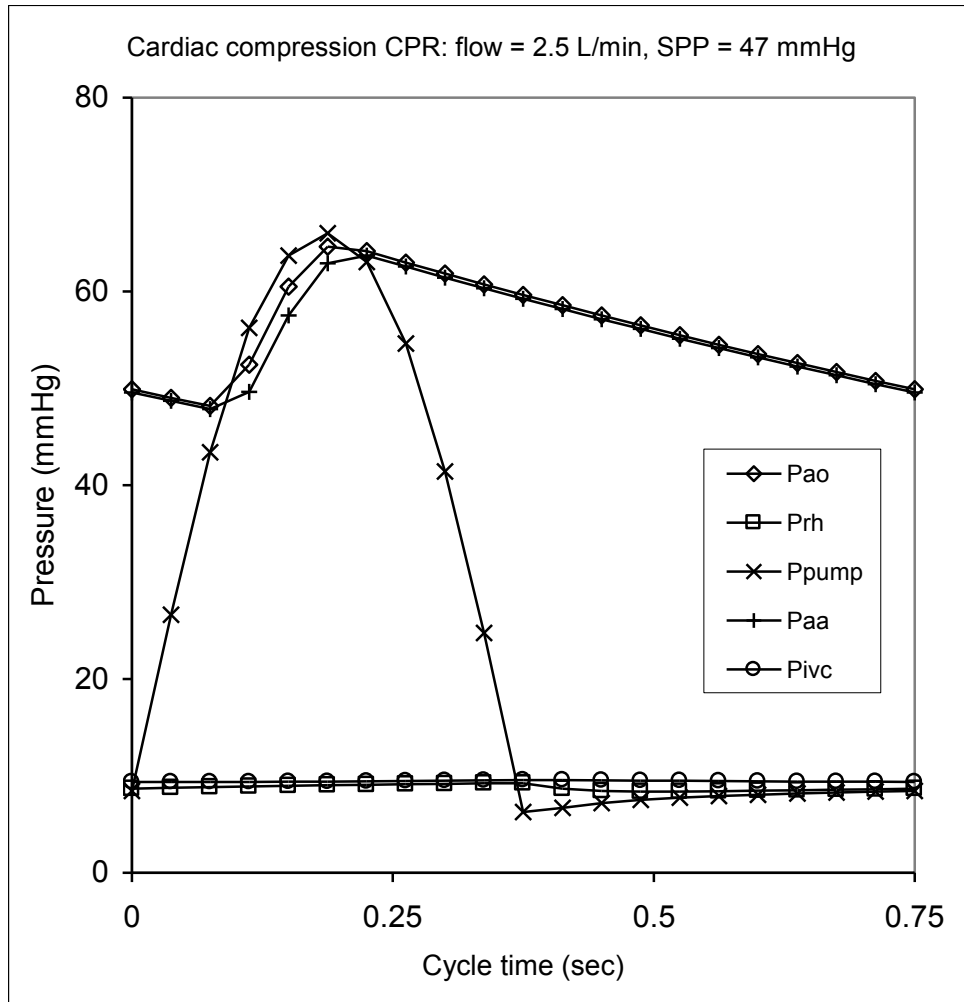


Figure 2. Pressures in a mathematical model of the normal adult human circulation during cardiac arrest and CPR with a pure cardiac pump mechanism. The compression rate is 80/min. Pressures are defined as in Figure 1.

ACD-CPR

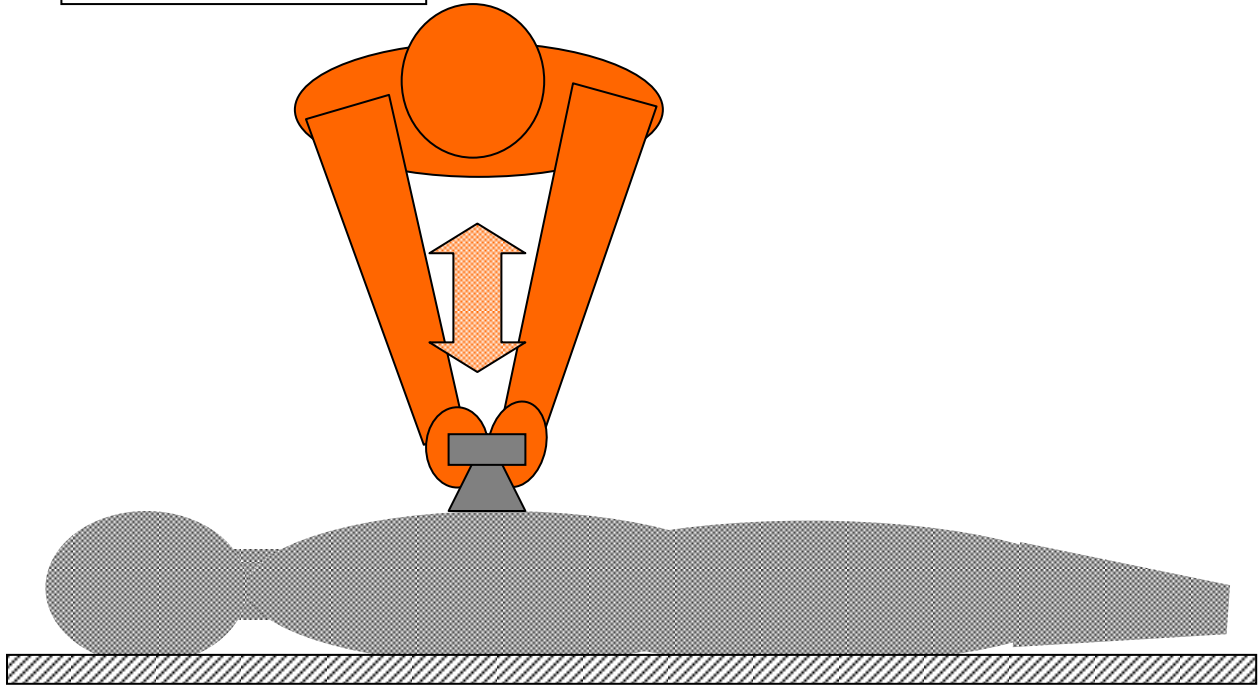


Figure 3. Sketch of active compression-decompression CPR using a plunger-like device.

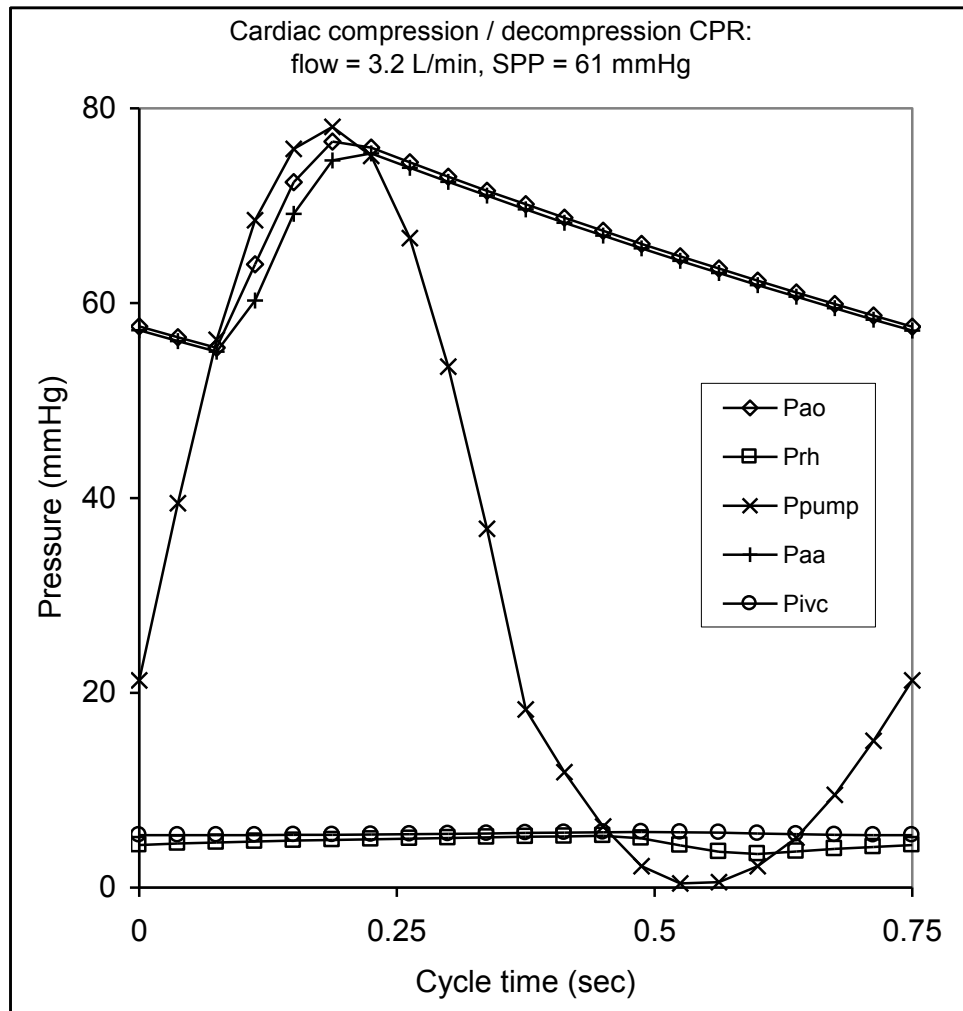


Figure 4. Pressures in a mathematical model of the normal adult human circulation during cardiac arrest and active compression-decompression CPR with a pure cardiac pump mechanism. The compression rate is 80/min. Pressures are defined as in Figure 1. Maximal chest compression pressure is + 60 mmHg. Maximal decompression pressure is -20 mmHg.

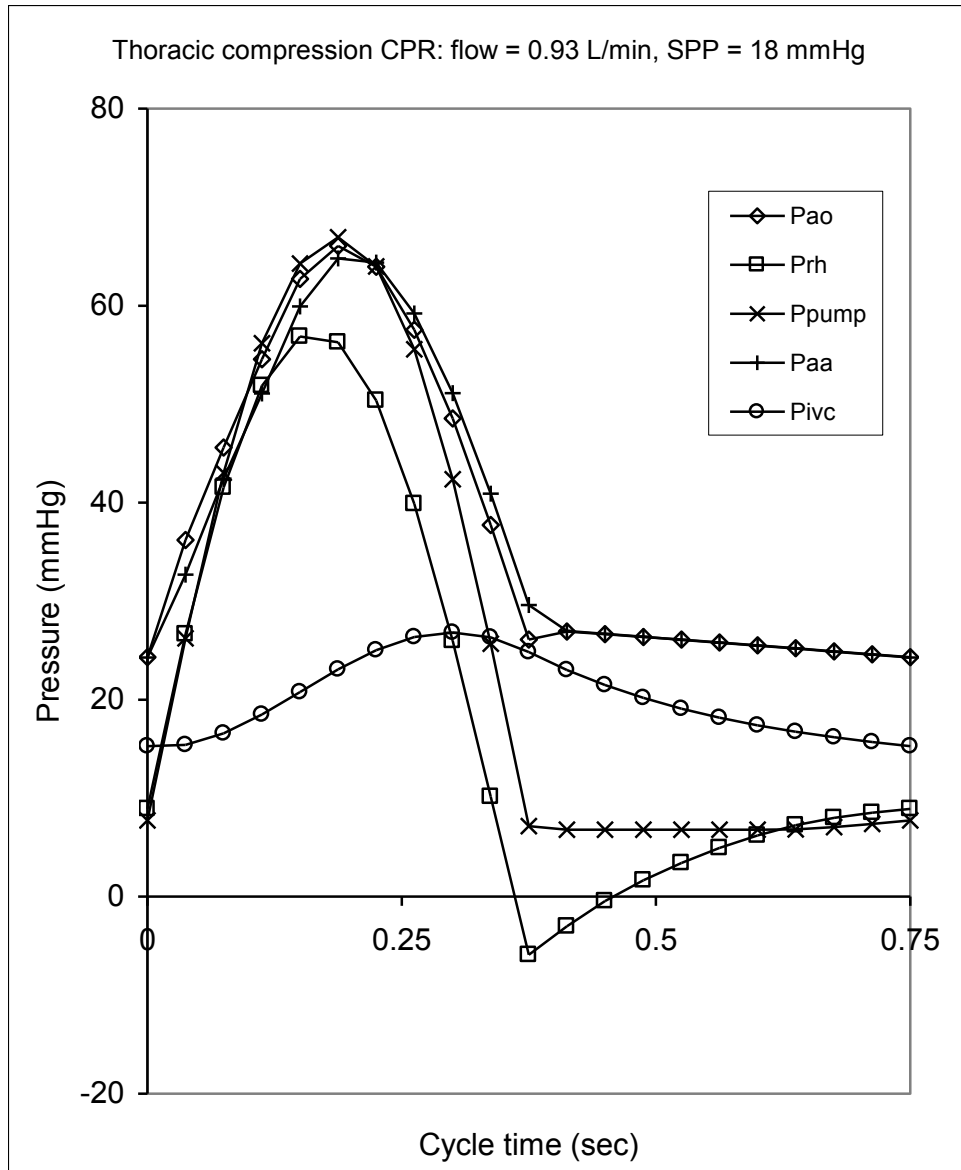


Figure 5. Pressures in a mathematical model of the normal adult human circulation during cardiac arrest and CPR with a pure thoracic pump mechanism. The compression rate is 80/min. Pressures are defined as in Figure 1. Maximal chest compression pressure is +60 mmHg.

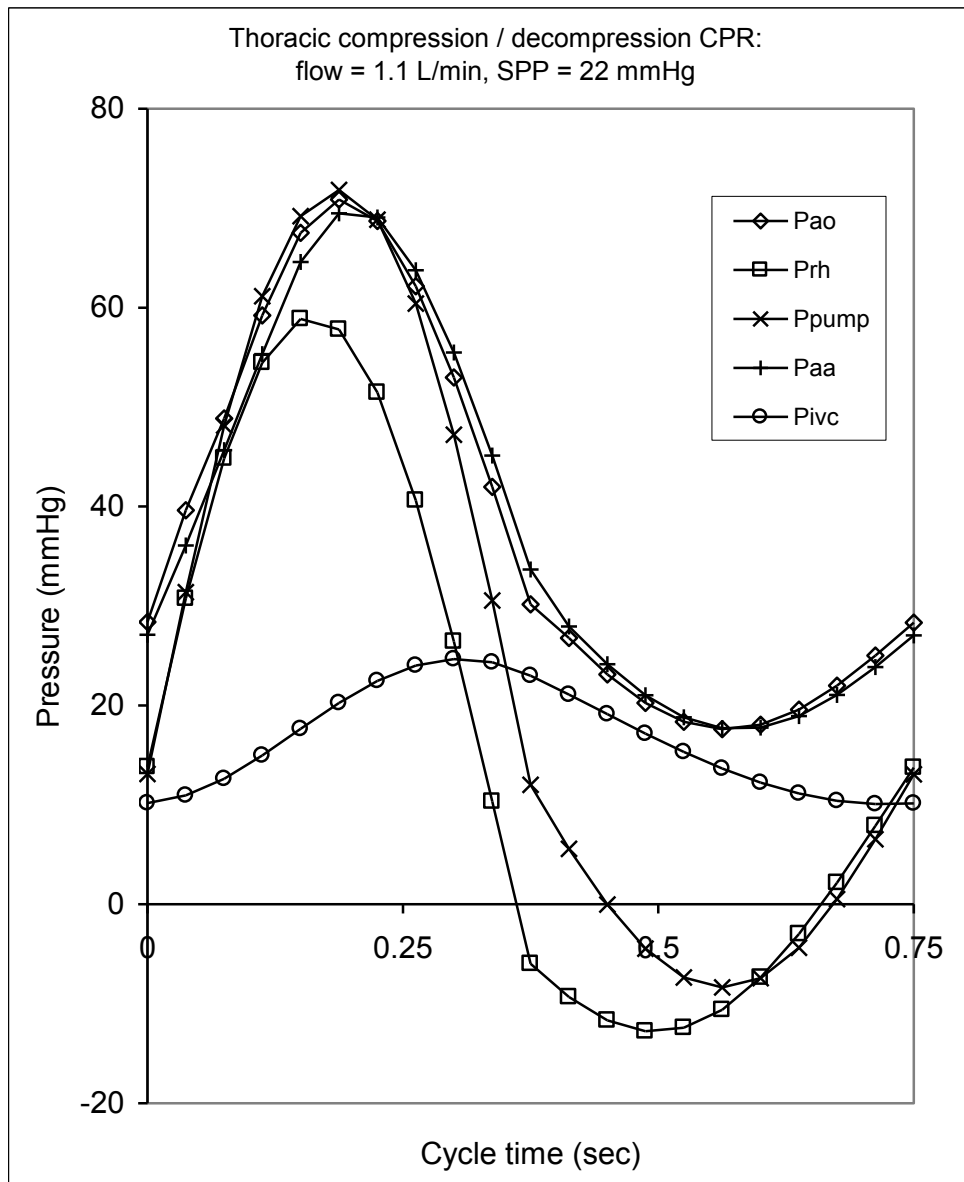


Figure 6. Pressures in a mathematical model of the normal adult human circulation during cardiac arrest and active compression-decompression CPR with a pure thoracic pump mechanism. The compression rate is 80/min. Pressures are defined as in Figure 1. Maximal chest compression pressure is +60 mmHg. Maximal chest decompression pressure is -20 mmHg.

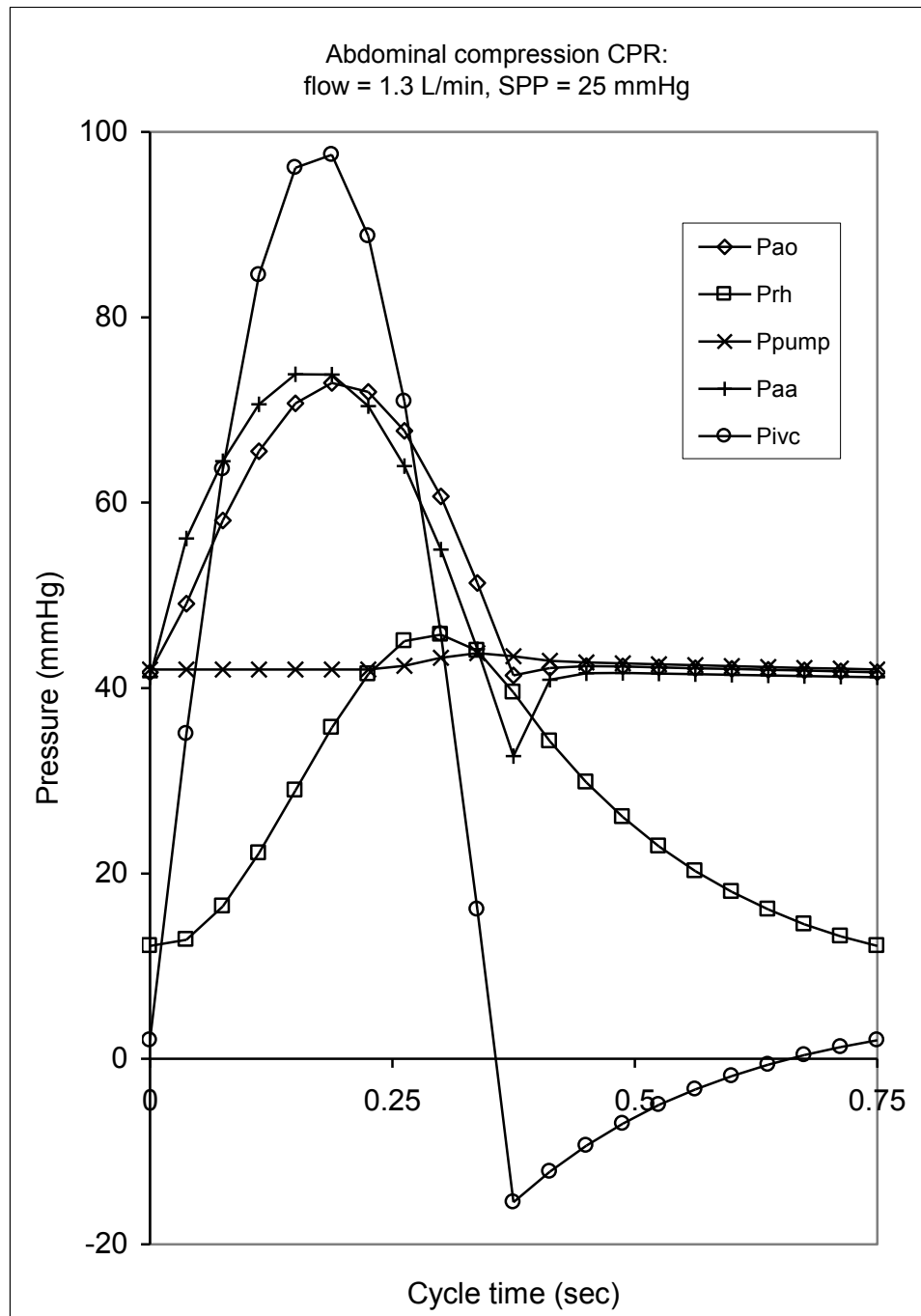


Figure 7. Pressures in a mathematical model of the normal adult human circulation during cardiac arrest and CPR with a pure abdominal pump mechanism. The compression rate is 80/min. Pressures are defined as in Figure 1. Maximal abdominal compression pressure is +110 mmHg.

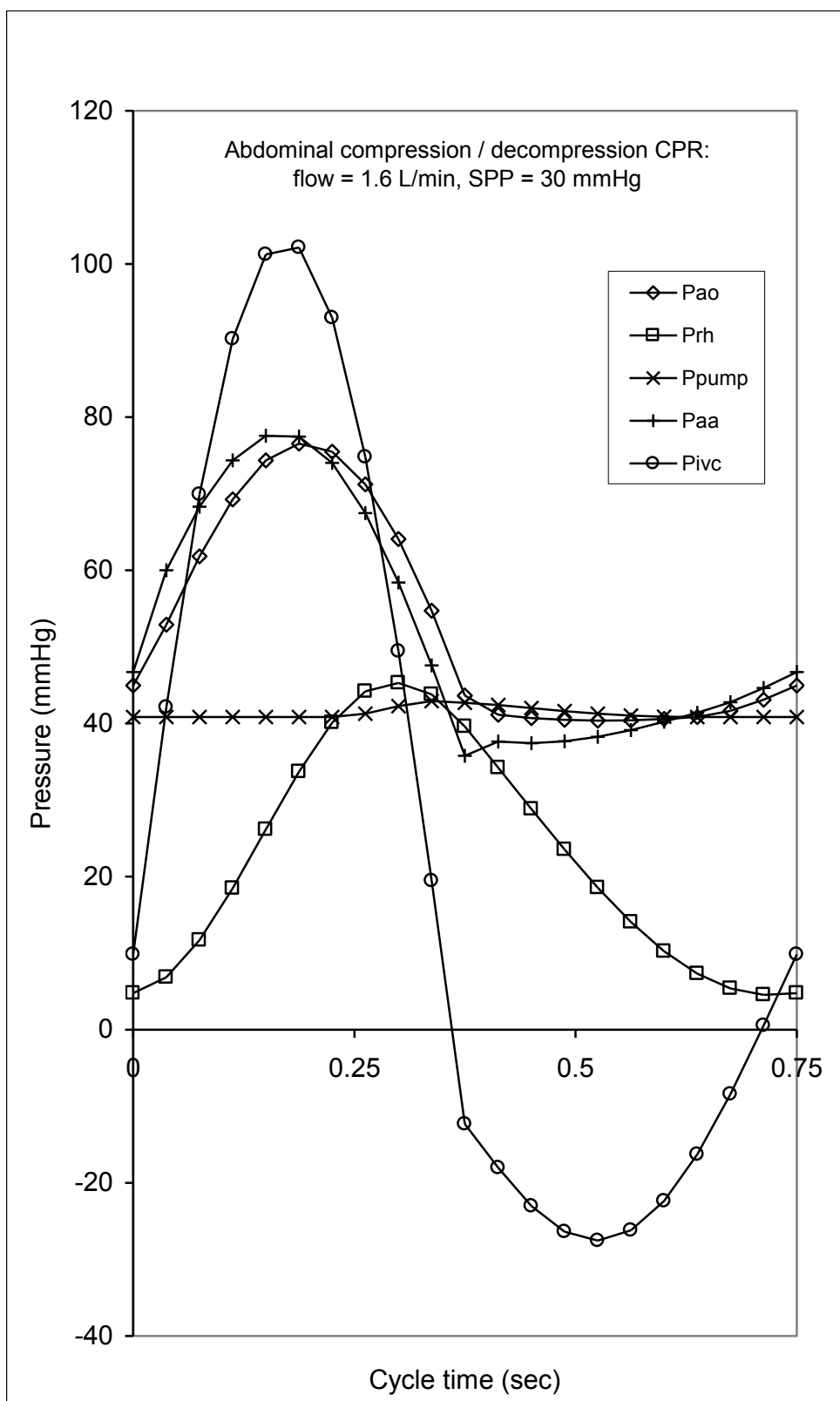


Figure 8. Pressures in a mathematical model of the normal adult human circulation during cardiac arrest and active compression-decompression CPR with a pure abdominal pump mechanism. The compression rate is 80/min. Pressures are defined as in Figure 1. Maximal abdominal compression pressure is +110 mmHg. Maximal abdominal decompression is -30 mmHg.

IAC-CPR

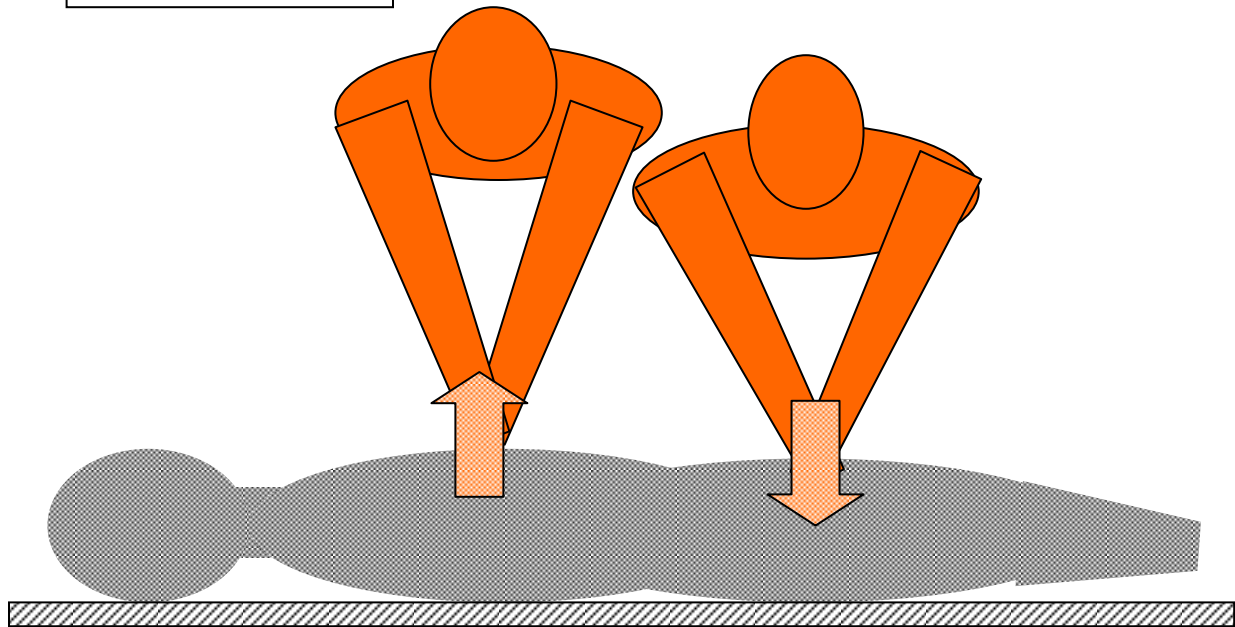


Figure 9

Figure 9. Sketch of interposed abdominal compression CPR.

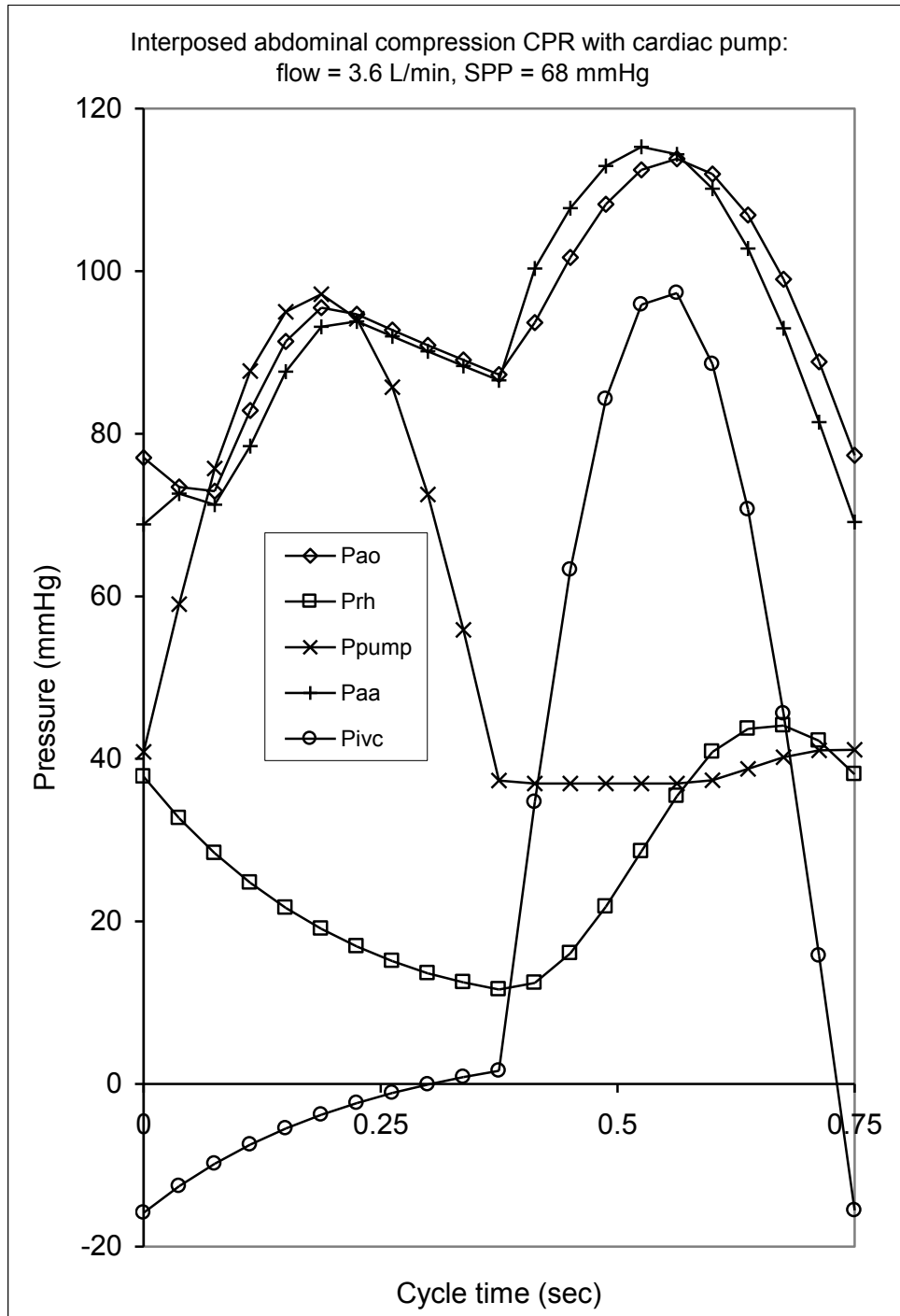


Figure 10(a). Pressures in a mathematical model of the normal adult human circulation during cardiac arrest and interposed abdominal compression CPR with a pure cardiac pump mechanism. The compression rate is 80/min. Pressures are defined as in Figure 1. Maximal chest compression pressure is +60 mmHg. Maximal abdominal compression pressure is +110 mmHg.

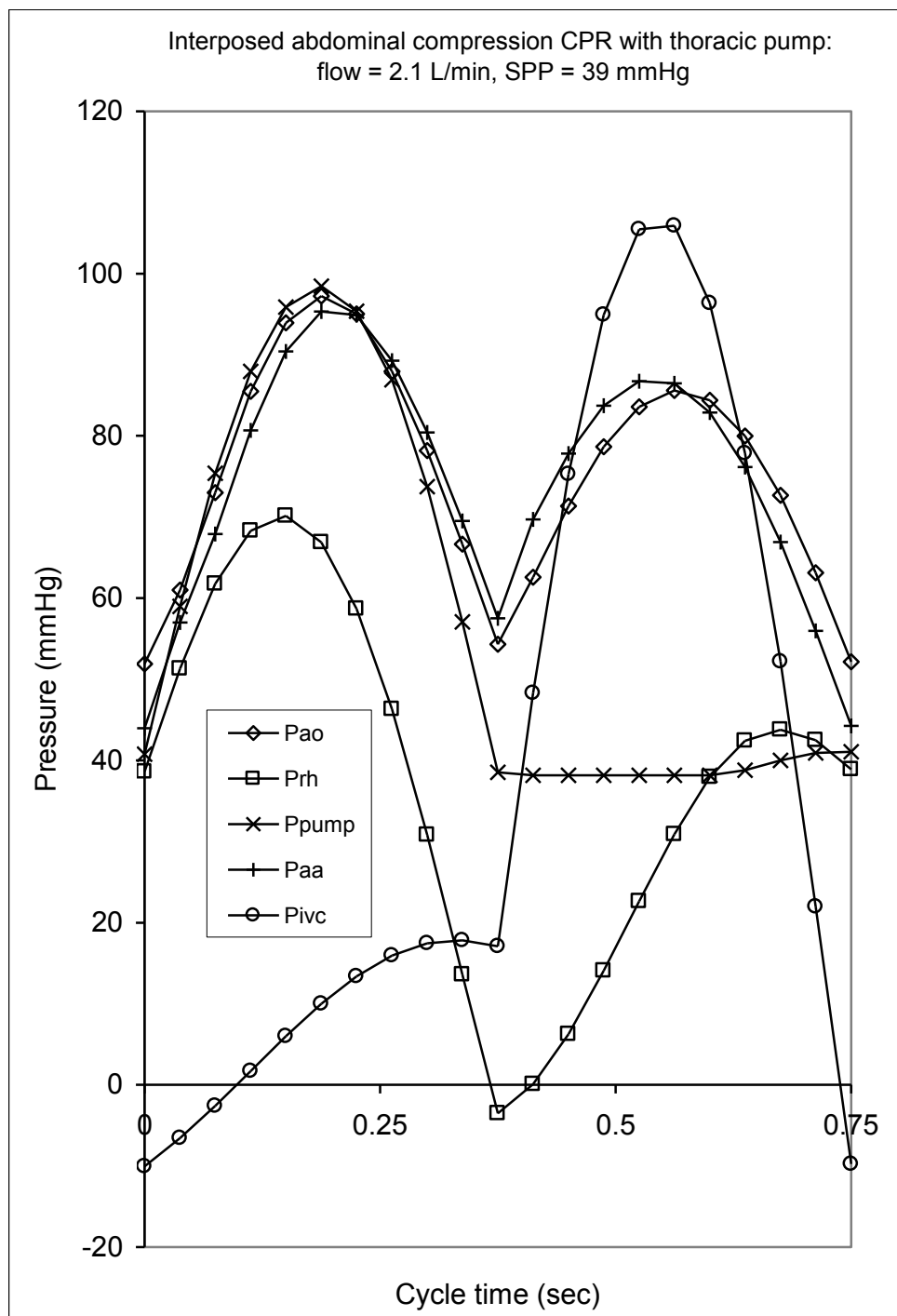


Figure 10(b). Pressures in a mathematical model of the normal adult human circulation during cardiac arrest and interposed abdominal compression CPR with a pure thoracic pump mechanism. The compression rate is 80/min. Pressures are defined as in Figure 1. Maximal chest compression pressure is +60 mmHg. Maximal abdominal compression pressure is +110 mmHg.

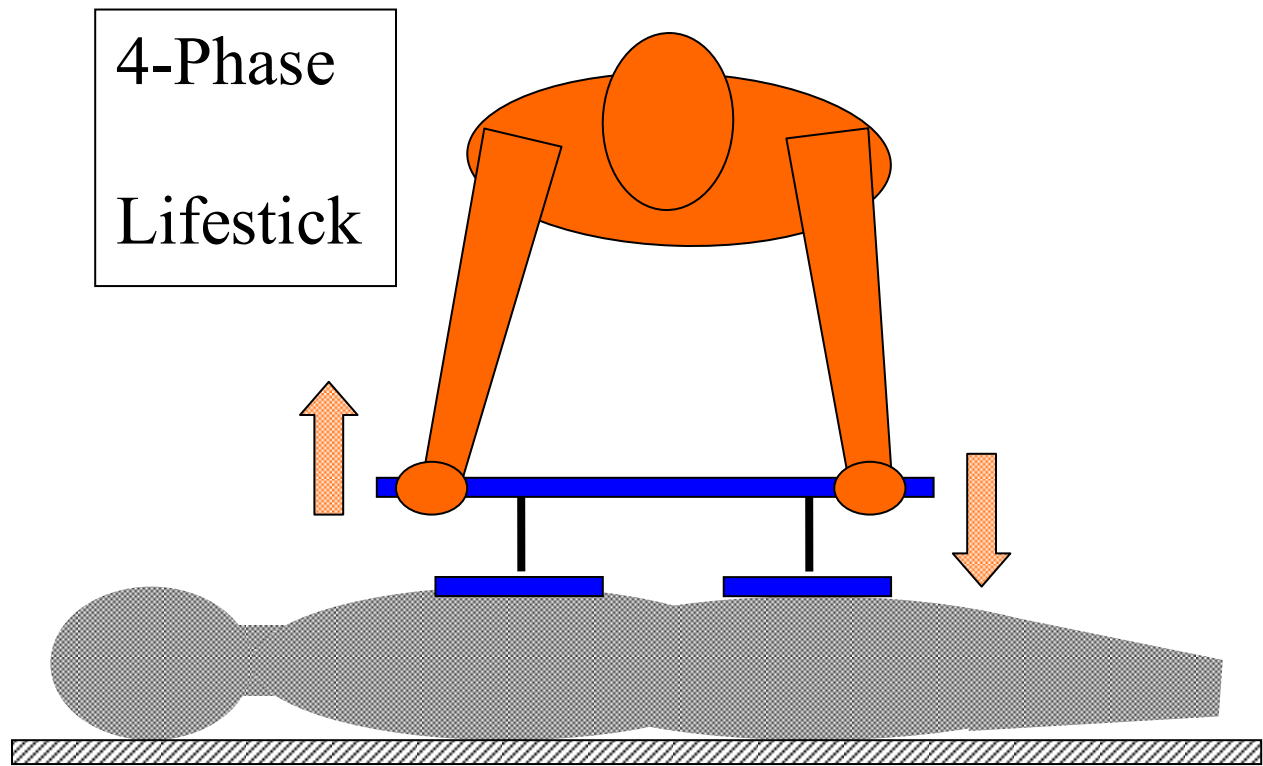


Figure 11. Sketch of Lifestick CPR.

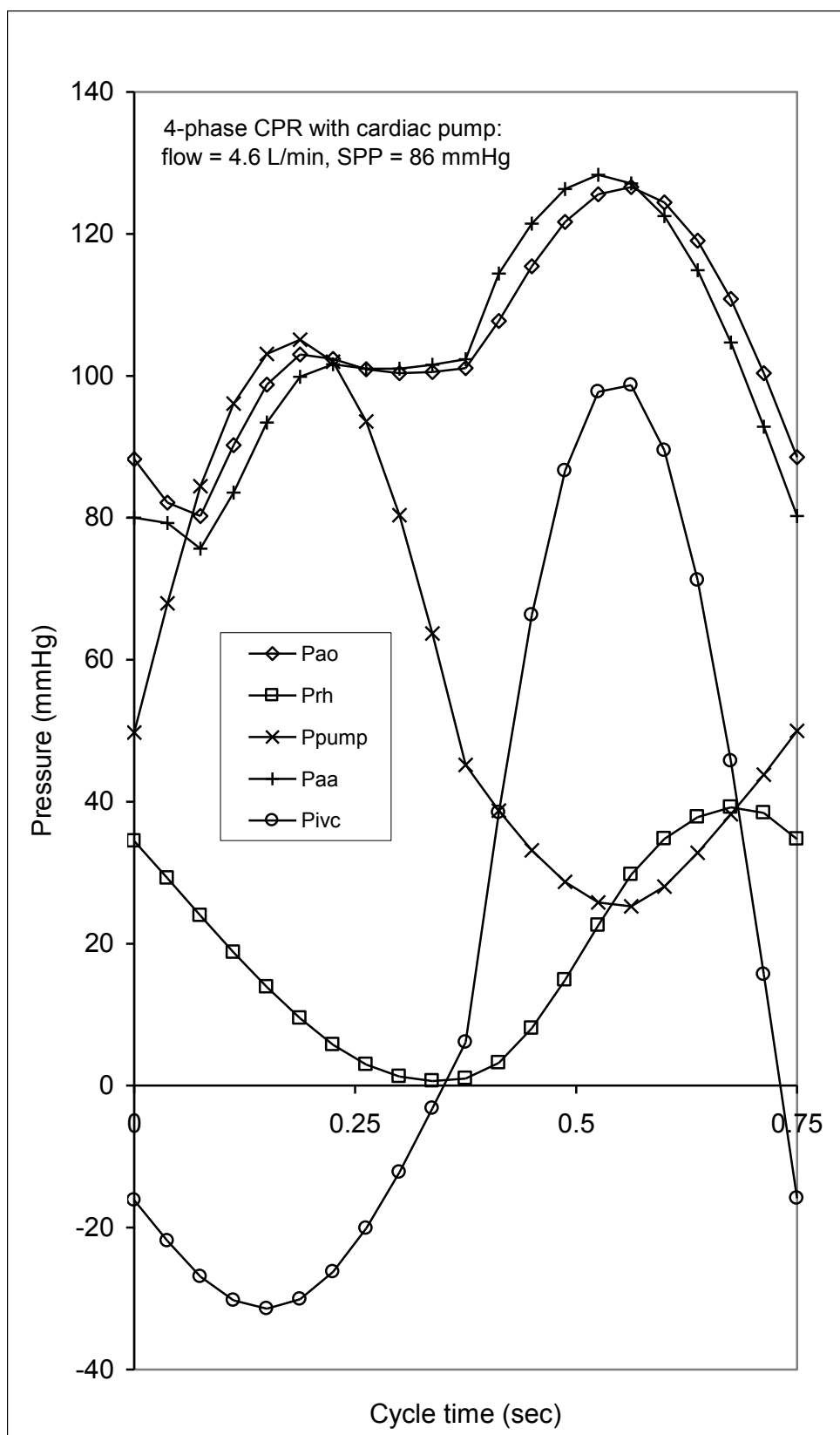


Figure 12(a). Pressures in a mathematical model of the normal adult human circulation during cardiac arrest and 4-phase CPR with a pure cardiac pump mechanism. The compression rate is 80/min. Pressures are defined as in Figure 1. Maximal chest compression pressure is +60 mmHg. Maximal abdominal compression pressure is +110 mmHg. Maximal chest decompression pressure is – 20 mmHg. Maximal abdominal decompression pressure is –30 mmHg.

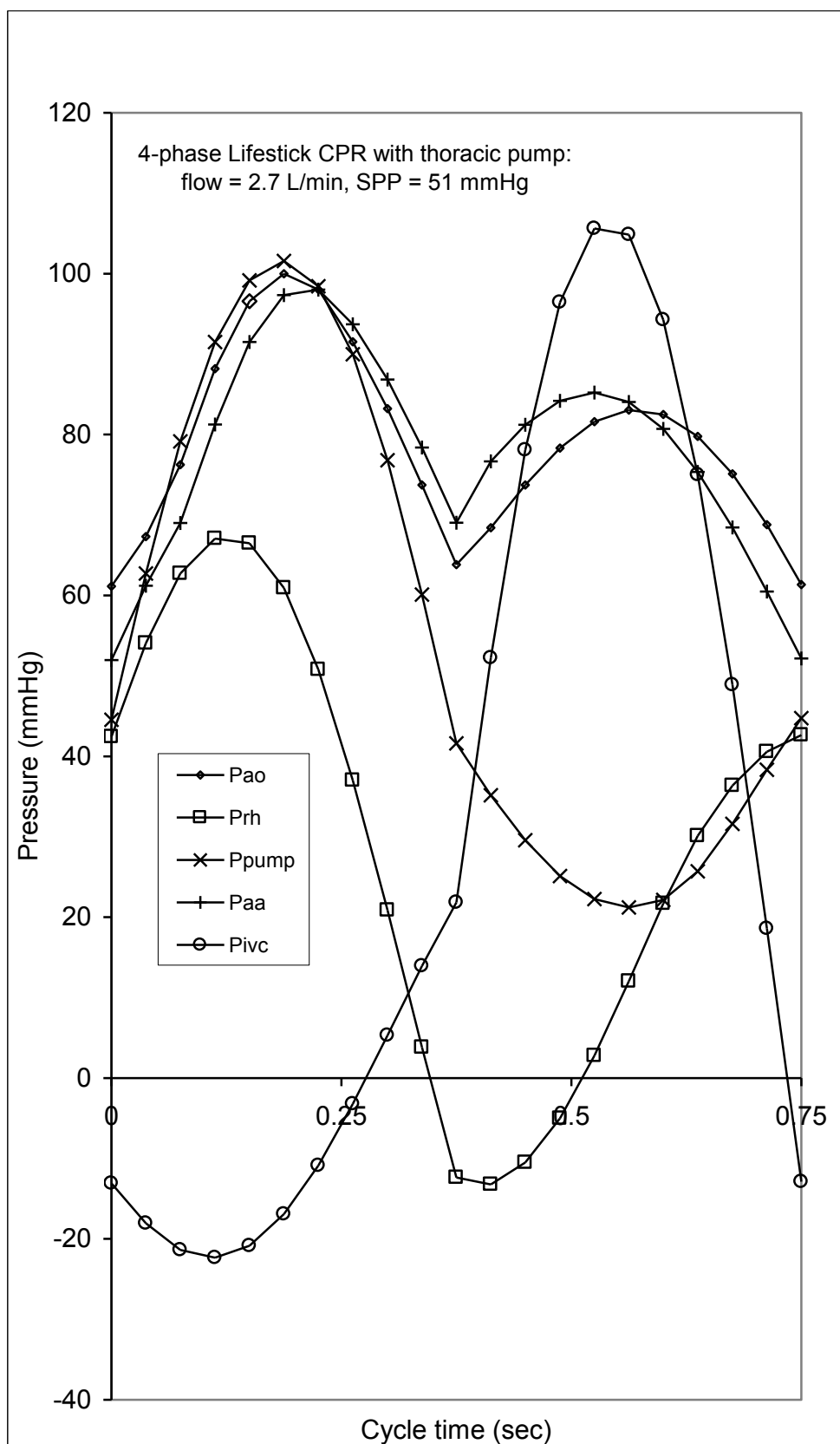


Figure 12(b). Pressures in a mathematical model of the normal adult human circulation during cardiac arrest and 4-phase CPR with a pure thoracic pump mechanism. The compression rate is 80/min. Pressures are defined as in Figure 1. Maximal chest compression pressure is +60 mmHg. Maximal abdominal compression pressure is +110 mmHg. Maximal chest decompression pressure is – 20 mmHg. Maximal abdominal decompression pressure is –30 mmHg.